National Aeronautics and Space Administration

Cryogenic Fluid Management Technology Development for Nuclear Thermal Propulsion

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Shaping the Future of Aerospace

Agenda

- **Introduction**
- **Environments**
  - Radiation
    - Nuclear heating mechanisms and profile
    - Thermal mixing and stratification
    - Mitigation strategies
  - Natural
    - Earth atmosphere and low earth orbit
    - Deep space
    - Other celestial body
- **Cryogenic Fluid Management Technology**
  - Passive systems
  - Active systems
  - Low leakage valves
- **Conclusions**

Introduction

- **Cryogenic Fluid Management is a key technology area for enabling long duration deep space exploration**
  - Manned and large payload
- **Natural environments result in significant thermal challenges**
- **Nuclear propulsion systems pose additional thermal challenges due to the radiation flux from the reactor**
- **Even small loss rates of propellant are significant over a long duration missions**
- **Technologies exist for managing heat leak into cryogenic fluids**
  - (e.g. insulation, cooling systems, low conductivity materials)
  - Not yet adequate for deep space exploration such as a manned mission to Mars

Environments

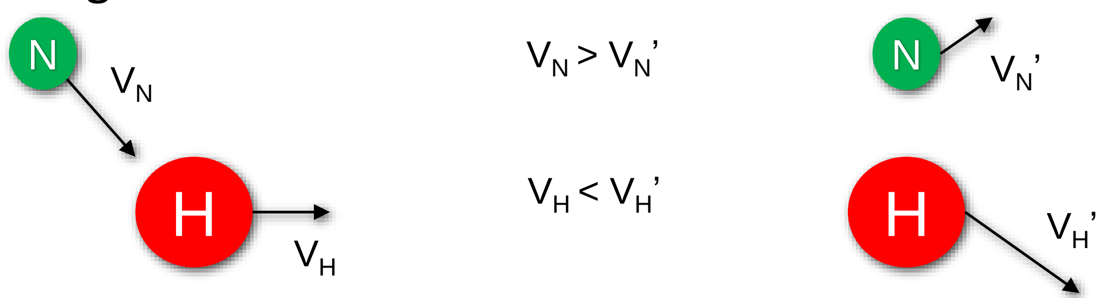
Radiation

Radiation Environment

- **Absorption of nuclear radiation produced by fission can result in degradation or damage to structural components**
- **Each interaction ultimately produces heat in the surrounding material**
  - Such heating is a concern for maintaining supplies of cryogenic propellant
- **The propulsion system must be designed to minimize the thermal burden that can result in cavitation at the pump or increased boil-off of stored propellant.**

Nuclear Heating Mechanisms - Neutrons

- **Primary concerns for nuclear heating are from gamma ray photons and fast neutrons exiting the core region**
- **Fission produces high energy (fast) neutrons**
  - Higher mean free path than lower energy particles
  - Energy shed through elastic collisions, after which probability of further interaction increases
- **Due to its size, hydrogen readily absorbs the energy of neutrons**
  - Hydrogen is often chosen as the propellant to increase Isp
  - Heavy nuclei absorb less energy in an elastic collision
  - Fast neutrons tend to travel through metals to deposit their energy in the liquid Hydrogen

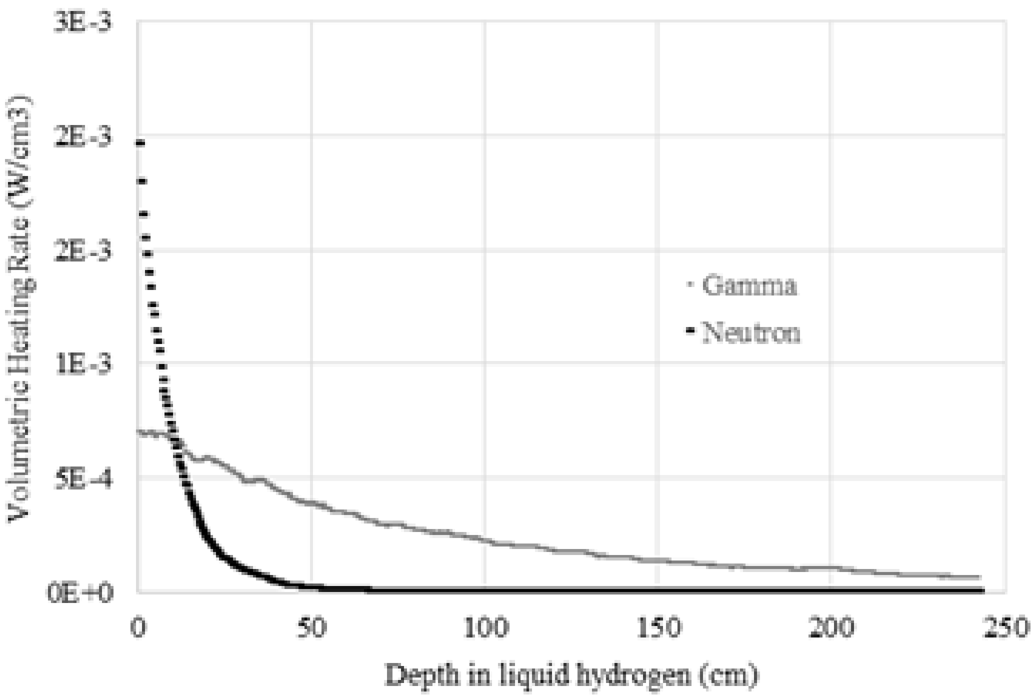


Nuclear Heating Mechanisms – Gamma Rays

- **Gamma rays produced in the reactor and through secondary radiation**
  - Secondary radiation may result after a lower energy neutron is absorbed by an atomic nuclei
  - Secondary radiation is a major source of gamma rays in nuclear thermal propulsion systems
- **Gamma rays interact more readily with heavier nuclei such as the metal structure**
  - Pass through lower density material easier than neutrons

Nuclear Heating Profile

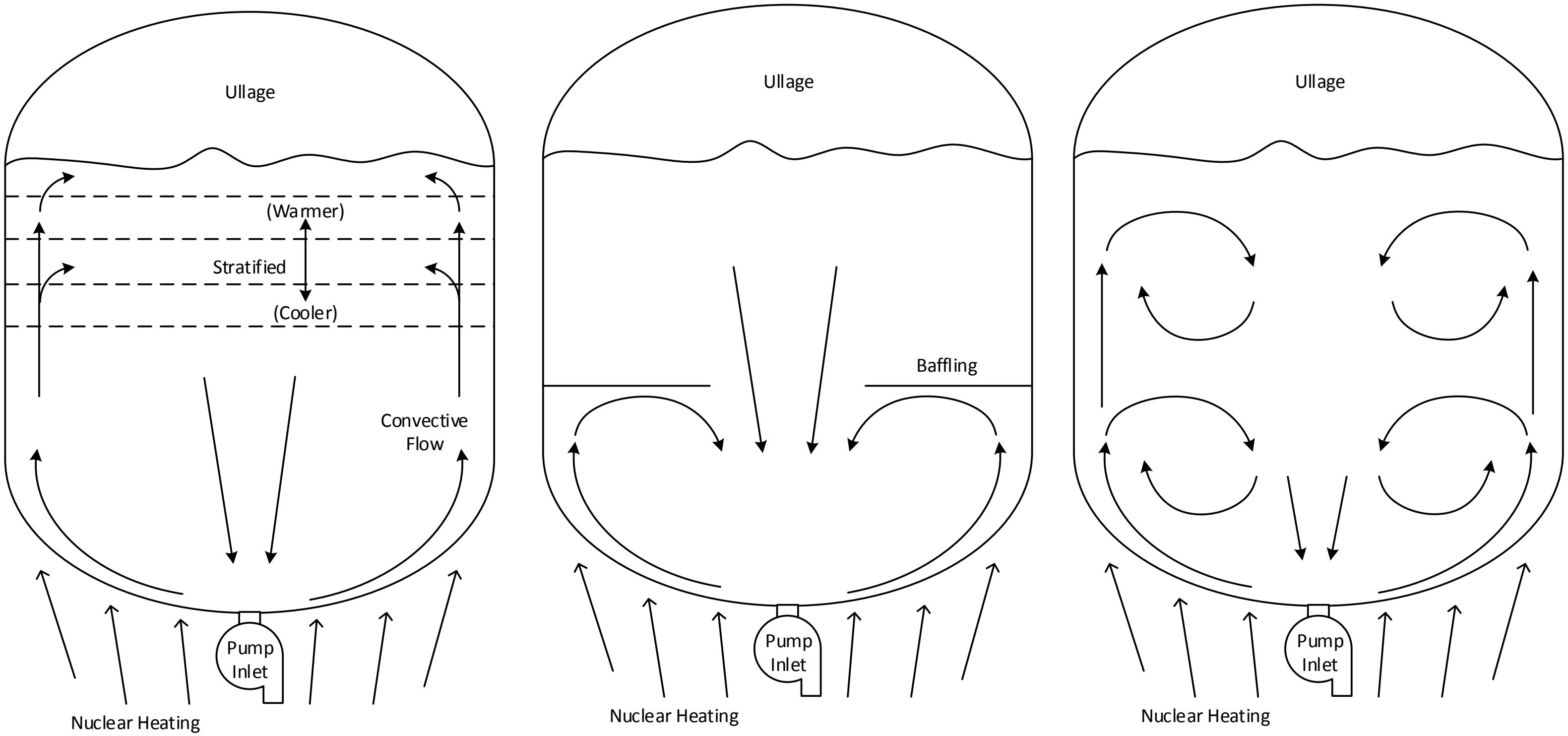
- Neutron energy deposited largely into the 50 cm of the liquid hydrogen closest to the engine
- Gamma rays are absorbed throughout the tank volume and produce more of a bulk heating effect
- Indirect heating also results from nuclear heated structural components and tank walls
- The energy deposited by neutrons at the engine-facing surface is several times that deposited by gamma rays
- The figure is an example nuclear heating profile comparing neutron and gamma contributions for a 3-engine cluster with cylindrical LiH-S.S. and tungsten shield



Thermal Mixing and Stratification

- **Localized nature of nuclear heating results in a complex heat distribution that changes through the duration of an engine burn**
- **Vehicle acceleration coupled with density gradient due to heating induces convective flows**
  - Phenomenon is also seen in traditional externally heated tank walls in spacecraft
- **Dynamics high dependent upon multiple factors such as flow rate of propellant exiting the tank, radiation flux entering the aft face of the tank, and any flow control devices or liquid acquisition devices**
- **Accumulation of stratified layers can possibly be avoided with careful design of baffling and mixing devices inside of the propellant tank.**

Thermal Mixing and Stratification



(Left) Thermal stratification of heated propellant near the ullage interface or fore-end (top) of tank. Propellant temperature is critical near end of burn.

(Center) Local mixing forces immediate consumption of heated propellant and prevents buildup of heated fluid near end of burn.

(Right) Complete mixing homogenizes thermal distribution in the tank.

Mitigation Strategies

- **Shielding**
  - Determination of maximum permissible flux will drive design
  - High mass penalty
  - Large diameter required for shadow shield
- **Repurpose boil-off**
  - Some boil-off hydrogen may be vented to a combustion system (provided an oxidizer) to generate power or ullage gas
    - Thus turning the boil-off from waste into useful by product
    - Boil-off allowance will decrease shielding requirements

Mitigation Strategies

- **Increase standoff distance between the engine and tank as well as decrease tank diameter at the aft face**
  - Mass and diameter of shield can be reduced by increasing distance between the engine and tank or by reducing the apparent diameter of the tank at the aft side

Sketch describing variable parameters of Monte Carlo calculation in Table 1. S = Standoff distance between nuclear engines and bottom of tank. D = Diameter of cryogenic storage tank, including 20 cm insulation thickness.

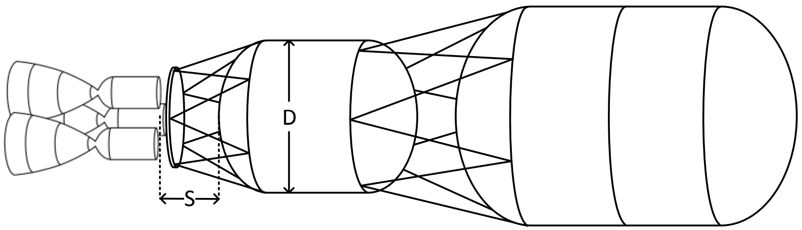


Table 1 – Calculated total heating rates in core stage tank for varying tank diameter and standoff distance. Identical shielding in all cases.

Standoff b/w Tank and Engines		3 m	6 m	9 m
Tank Diameter	6 m	**10.9 kW**	**3.7 kW**	**1.5 kW**
	7.6 m	**24.1 kW**	**7.5 kW**	**3.2 kW**
	8.4 m	**32.3 kW**	**10.0 kW**	**4.2 kW**

Environments

External

Earth Atmosphere and Low Earth Orbit

- **The large quantities of propellant and equipment needed for a deep space manned mission will require multiple launches and an on orbit assembly of a exploration vehicle**
  - Long loiter times will likely be required to accommodate launch frequency and operations
- **Examples of thermal factors**
  - Aerodynamic heating resulting from launch environment
  - Heating from rarefied gas molecules
  - Radiation reflected off the Earth
  - Solar radiation
  - Earth’s magnetic field and charged particle interaction

Deep Space

- **Beyond Low Earth Orbit radiation is the primary source of thermal energy**
  - Background radiation will deposit energy into the vehicle and crygens
- **Sources of deep space radiation**
  - Cosmic microwave background radiation
    - Uniform background radiation, relic of big bang
  - Cosmic radiation generated outside the solar system
    - High energy particles such as protons, alpha particles, beta particles and some heavier nuclei
  - Solar radiation
    - Photons
    - Solar wind
      - Charged (high energy) particles propelled by the sun's magnetic field

Other Celestial Body

- **Celestial bodies that are destinations of exploration missions will have unique thermal environments that a spacecraft must be designed to handle**
- **While strengths and interactions will be different, some of the same factors must be accounted for to determine the thermal environment as were for low earth orbit**
  - E.g.
    - Aerodynamic heating resulting from launch environment
    - Heating from rarefied gas molecules
    - Radiation reflected off the Earth
    - Solar radiation
    - Earth’s magnetic field and charged particle interaction

Cryogenic Fluid Management Technology

Cryogenic Fluid Management (CFM)

- **Cryogenic propellants have been around for decades**
  - Primarily on board launch vehicles
  - Launch vehicles must maintain their propellants for timeframes on the order of hours
  - Current capabilities are 9-17 hour durations with 30% per day boil-off
  - A Mars exploration mission is expected to take 18 to 24 months
- **Long duration missions such as satellites and probes have used other forms of propulsion**
  - Hypergolic
  - Electric propulsion
- **The loss of cryogenic propellants must be reduced to enable deep space missions**

Passive Systems

- **Thermal barriers that reduce conductivity and radiation flux to the tank**
- **Spray on Foam Insulation (SOFI)**
  - Best performance in atmosphere
- **Multi-Layer Insulation (MLI)**
  - Thin layers of high reflectance metal that act as radiation shield
  - multiple double aluminized Mylar (DAM) radiation shields with Dacron net spacer material between shields
  - Less effective in atmosphere, better in vacuum
- **Low conductivity support structures**
  - Reduce conduction

Passive Systems

- **Advanced MLI**
  - Low conductivity spacers
    - Replace conventional netting
      - 40-60% lower heat flux than conventional MLI
  - Load responsive spacers and light weight vacuum shell for launch vehicle applications
    - Two orders of magnitude decrease heat leak and one order of magnitude decrease in mass
  - Variable density MLI
    - Greater spacing between inner layers to reduce conduction
    - Reduces mass and heat leak
    - Larger but fewer perforations for venting
      - Reduces radiation heat transfer through the MLI
    - Decreased heat leak by 41% compared to standard MLI for warm boundary condition of 305K and 25 fewer layers

Active Systems

- **Cryocoolers actively remove heat from propellant tanks**
  - Began flying in the early 1990's
  - Primary flight application has been for instrumentation
    - 55-150 K cooling temperatures
    - Reliability has improved with many long lived systems on orbit
    - Ex:
      - JPL Sorption cryocooler for the PLANCK space telescope
      - 50-80 K Astrium for Helios 2A and 2B
- **Cryocooler development is headed to larger systems at lower temperatures**
  - 10 to 20 K range
  - Larger heat removal capabilities
    - 20 K at 20 W goal of turbo-brayton cycle cryocooler being developed by Glenn Research Center and Creare Inc.
    - 20 K cooling temperature range is needed for liquid Hydrogen
    - Larger heat removal at higher efficiencies is needed for maintaining cryogenic propellant conditions on future long duration mission vehicles

Low Leakage Valves

- **Valve, disconnects, and other fluid control devices of a size relative to launch vehicles or a NTR Mars exploration vehicle have leakages on the order of 100 SCIM**
  - 10 components over a 3 year mission could lose on the order of 100,000 lbs of propellant
    - Compensating for this represents significant mass growth
    - Also represents risk of running out of propellant
  - Seats, which break and remate as the valve opens and closes, are the primary source of leakage
    - Consistent sealing difficult
    - Contamination is an issue
    - Flat seat design and large load in state of the art
- **Leakage many orders of magnitude lower than state of the art must be developed**
  - Marshall Space Flight Center working toward 10^{-3} SCIM
    - Large spherical seat design and a differential angle seat design in development

Conclusion

- **Significant challenges to storing cryogenic propellants on long duration missions must be addressed**
  - Radiation complicates an already significant problem
- **Heat absorption and propellant leakage must be managed to maintain propellant conditions and availability**
- **It is important that the community invest in technologies such as MLI, cryocoolers, and low leakage valves**
  - Long term cryogenic fluid storage capabilities are essential to future exploration missions that will take astronauts to Mars or other distant destinations